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Relationships of Rapidly Solidified Al-Mg-Li Alloys" by W. Wang and N. J. Grant, was also initiated under this contract, but was far from being completed within the one-year span. Nevertheless, since the research was started under the DARPA (ARO) contract, the very interesting results of the research are summarized in this final report. A third study, which was initially started as an ONR (DARPA) program, was an analytical study which took about four years to complete. Based on the content of this study and its initiation under DARPA support, the program was continued as part of this effort. The study was recently completed under other funding. This study was entitled "Notched Tensile Properties of Rapidly Solidified and Ingot-Based Aluminum Alloys" by S. Kang and N. J. Grant. The paper was presented at the Rapid Solidification Conference at NBS, held in Dec. 1982.

ADVANCED ALUMINUM-LITHIUM BASE ALLOYS
PRODUCED BY RAPID SOLIDIFICATION FROM THE MELT

Research Program at

Massachusetts Institute of Technology

From February 8, 1981 to February 7, 1982

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FINAL REPORT

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ADVANCED ALUMINUM-LITHIUM BASE ALLOYS PRODUCED BY RAPID SOLIDIFICATION FROM THE MELT

SUMMARY

Three research tasks were supported to varying degrees under this program and contract support. One of them was fairly well advanced on termination of the contract one year after its initiation. This work was continued and has resulted in a paper entitled "Lithium-Containing 2024 Aluminum Alloys Made from Rapidly Solidified Powders," by W. Wang and N. J. Grant. The paper was presented at the Second International Conference on Al-Li Alloys, held at Monterey, Calif. in April 1983. A preprint is attached.

A second study, entitled "Structure-Property Relationships of Rapidly Solidified Al-Mg-Li Alloys" by W. Wang and N. J. Grant, was also initiated under this contgract, but was far from being completed within the one-year span. Nevertheless, since the research was started under the DARPA (ARO) contract, the very interesting results of the research are summarized in this final report. The research results are now being prepared for publication. When preprints are available in the next several nmonths, copies will be mailed to ARO and DARPA in order that the findings and conclusions can be made available to interested persons and incorporated into appropriate records.

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reprints of the paper at which time copies will be made available to DARPA and ARO. In the meantime a preprint is attached to this report.

Discussion of the Research Results

1. Lithium-Containing 2024 Aluminum Alloys Made from Rapidly Solidified Powders, by W. Wang and N. J. Grant.

Fine powders were produced by the MIT Ultrasonic Gas Atomization Process (USGA) of three lithium-containing 2024 aluminum alloys. Because the powders were melted, atomized, and cooled to room temperature in an inert atmosphere, and had nominal exposure to air in subsequent handling (packing for temporary storage and canning prior to extrusion), the powders were not treated for hydrate decomposition. Such decomposition treatments require temperatures in excess of 500°C and lead to some coarsening of the structure as well as increased oxide content. This situation is worse in the 2024 class of alloy because solution temperatures are generally less than 500°C. As seen in the attached preprint of this work, one alloy was incorrectly held at 500°C and showed severe coarsening of the $CuMgAl_2$ phase.

There were several aims in conducting this research:

a) The effect of the Cu:Li ratio was of interest since that ratio, for Li contents from about 1 to 3%, controls the phases at equilibrium, therefore changes the strengthening mechanisms as well.

b) The role of Mn and Cd additions to this alloy. These additions were originally made to ingot-based alloys to improve grain size control (Mn) and to modify the aging process (Cd). Since Cd is a heavy element, relatively toxic on exposure by humans, and expensive, its elimination is highly desirable. Mn on the other hand is a heavy element; its elimination would be desirable for density reasons.

c) A comparison of property data was planned between these alloys produced by USGA (10^4-10^5 K/s solidification rate) and splat quenching (10^6 K/s, work by Sankaran and Grant).

Excellent properties were obtained by the two alloys which were correctly processed (without the hydrate decomposition treatment). Tensile yield and ultimate were significantly better than for IM 2024, and when corrected for density had a specific tensile strength of about 84,000 psi. Elongation values were from 8 to 12% and reduction of area values were in the range 13 to 20%. With these high ductililty values it was no surprise that notched tensile tests showed notch strengthening. Excellent fracture toughness values were recorded in the range 30.8 to 33.9 ksi $\sqrt{in}$..

In reversed bending fatigue tests, in air, the RS-PM 2024 + 1.63% Li alloy shows, for 10^7 cycles, a stress improvement of about 30% over IM 2024, uncorrected for density. Finally, in fatigue crack growth rate tests the RS-PM alloys were significantly better than IM 2024, especially at low crack growth rates.

In terms of the Cu:Li ratio, at about 4% Cu, strengthening appears to be enhanced by the presence of the T_1 phase. Cu in excess of the solubility limit is not recommended.

The absence of Mn and Cd from Alloy No. 2 did not appear to change alloy behavior. The presence of these two alloying additions appears to be without benefit and probably could be omitted. Additional tests of a fairly abbreviated nature are suggested.

The USGA PM alloys, within experimental limits, appear to yield mechanical test data which are not different than those reported for the splat-quenched material. The total combination of processing variables used in making the alloys probably obscures any small differences which may exist due to the difference in solidification rates.

Other detailed data are available in the attached reprint.

2. <u>RS-PM AL-Mg-Li Alloys</u>, by W. Wang and N. J. Grant

A check of the literature shows a sharp bias for Al-Cu-Li alloys (X2020) over Al-Mg-Li alloys. This choice is based on the observation that copper-containing alloys undergo favorable aging from the precipitation of $CuAl_2$ as well as δ', whereas the Mg addition results primarily in a solid solution strengthening effect coupled with the same δ' aging feature.

Interestingly, the combined use of Cu + Mg (as with the 2024 type alloy: see item 1, above) seems to yield results between those of the X2020 and the Al-Mg-Li alloys.

Nevertheless the potential benefits from the use of Mg instead of Cu remain attractive, primarily because of important weight savings. One alloy was prepared, containing about 6.7% Mg and 1.64% Mg. The RS powders were prepared with the MIT USGA unit, producing excellent clean, spherical powders. The hot extrusion, at a 30:1 reduction ratio (area) produced a high quality bar. Again, a hydrate reduction treatment was not used.

A variety of heat treatments were studied based on preliminary hardness data, and the more promising treatments were then applied to test materials for a broad range of mechanical property evaluations. The best treatment was found to be solution at 450°C, 0.5h, WQ plus aging at 165°C, 10h, WQ. Yield strength was 61.2 ksi, ultimate was 76.7 ksi with a surprisingly high elongation of 11%. Corrected for density these values become 66.5 ksi yield and 83.4 ksi ultimate, very attractive values by any measure. The alloy is notch tough, though barely so, with a σ_{NTS}/σ_{YS} slightly greater than 1.0. Fracture toughness was poor, however, showing 19.7 ksi $\sqrt{in.}$ for the best condition. This we ascribe to the higher oxide content of the lithium-containing alloy. In reversed bending fatigue, the stress for 10^7 cycles is 30,000 psi, 20% better than for IM 2024, and 45% better than the value of 21,000 psi reported for the Soviet 01420 (IM) Al-Mg-Li alloy.

Our tentative conclusions based on studies of this Al-Mg-Li alloy are the following:

a) The RS-PM Al-Mg-Li alloy had a grain size of about 2μm. This fine grain size and constituent particle morphology were maintained at solution temperatures as high as 510°C for 0.5h.

b) The tensile properties of this alloy were quite insensitive to solution heat treat temperature from 400 to 510°C; thus low solution heat treatments can be used.

c) The low fracture toughness of the alloy is attributed both to localized shear deformation since the δ' phase is the predominant hardening phase, and to somewhat higher oxide content of the alloy associated with the lithium content.

d) The combination of strength and ductility for the RS-PM alloy is significantly better than for reported values for ingot material. If the fracture toughness can be improved by small modifications in composition and by better control of oxide content, the combination of density and sepcific properties could be of considerable interest for flight structures.

3. Notched Tensile Properties of Rapidly Solidified and Ingot Based Aluminum Alloys by S. Kang and N. J. Grant.

This study was not based on new research but was, instead, an analysis of the behavior of a broad range of aluminum alloys prepared by ingot technology and RS-PM techniques. We had been accumulating a significant amount of notch tensile data over several years, and were observing deformation and fracture patterns which were of great interest. Similar observations had been reported in the literature, primarily for ingot-based alloys, and this seemed the right moment to make comparisons with rapidly solidified PM alloys, both with and without lithium additions. The alloys which were examined and compared in this study are:

I/M 7075	RS-PM Al - 6% Mn
I/M Al-Li-Zr	RS-PM Al-Fe-Ni-Co

RS-PM X2020

RS-PM 2024 + Li

RS-PM X7091 (CT91)

RS-PM Al-Mn-Si

RS-PM 7075

RS-PM 7075 + 1 Zr + 1 Ni

The abstract and conclusions of the study follow.

ABSTRACT

In the development of high-strength aluminum alloys, the focus has been on alloy toughness as well as on strength, stiffness, fatigue behavior, corrosion, etc. In this paper, tension properties (σ_{UTS}, σ_{YS}, elongation) of various rapidly solidified (RS) and ingot-based aluminum alloys were examined and correlated with their notched tensile properties. Compiled data have shown that a linear relationship exists between the yield strength (σ_{YS}) and the notch yield ratio (σ_{NTS}/σ_{YS}); there is a poorer correlation between the ductility and the notch yield ratio. On the basis of Linear Elastic Fracture Mechanics (LEFM), the linear relationship is extended to relate σ_{YS} with K_{1C}. Under a given set of processing parameters, the extended equation, $K_{1C} = f(\sigma_{YS})$, could be utilized to indicate whether the toughness of an alloy (taking into account the related processing steps) in any way encourages or discourages further development.

Overall results indicate that RS materials are not better than I/M alloys in terms of toughness, and raise the questions of "why." One possible reason may be the presence of excess oxide in the form of continuous stringers in the inadequately worked RS-PM alloy. Tests are planned to attempt to evaluate the oxide issue.

CONCLUSIONS

- The notch yield ratio is equally sensitive to the yield strength over the entire range of yield values attainable by the alloy.
- The elongation values, on the other hand, show a sensitive region (high elongation region) and a nonsensitive region (low elongation region) with respect to the notch yield ratio.
- Each alloy type tends to have its own curve (slope and intercept) between the notch yield ratio and the yield strength such that the yield strength at a notch yield ratio of one (1) varies markedly from one alloy type to another. Further, the slopes of these curves seem to vary significantly among the alloys.
- Of particular interest, where test data are available for the same alloy in both ingot and RS-PM forms, the ingot and PM alloy points match up rather closely, leading to the conclusion (for now, at least) that RS alloys are not better (or worse) than similar I/M alloys in terms of notch toughness behavior. The reasons for this lack of superiority of one over the other (presumably PM over I/M) should be the basis of a careful study of processing variables to determine reasons for this behavior.